Advanced Industrial Archaeology: A new reverse-engineering process for contextualizing and digitizing ancient technical objects

Florent Laroche, Alain Bernard, Michel Cotte

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F.Laroche[1 2], A. Bernard[1], M. Cotte[2]
[1] Research institute in Communications and Cybernetics of Nantes (IRCCyN), Ecole Centrale, Nantes, France
[2] Centre François Viète for science and technical history, University, Nantes, France
florent.laroche@irccyn.ec-nantes.fr, alain.bernard@irccyn.ec-nantes.fr, michel.cotte@univ-nantes.fr

Abstract
Since virtual engineering has been introduced inside industries, time processes have been reduced and products are more adapted to customer needs. Nowadays, the DMU is the centre point for all teams: design, manufacturing, communication etc. However, physical mock-ups and prototypes are sometimes requested. Consequently, a back-and-forth action between the real and the virtual worlds is necessary.
Our research team has developed a reverse-engineering methodology for capturing technical characteristics of industrial objects but also for capitalizing knowledge and know-how which are required for contextualizing life cycles. More precisely, we work with ancient industrial machines. It is what we call Advanced Industrial Archaeology. Thanks to the coupling of different kinds of 3D digitalization technologies and CAD software, we are able to re-design old industrial objects and old processes.
To illustrate our proposal, we will describe one of the experiments we have done with a salt-washing machine which is nearly 100 years old: from the global 3D digitalization of the plant to precise parts design, we have rediscovered the enterprise process and understand its integration in the economic context.

Keywords
reverse-engineering, 3D digitalization, CAD, Advanced Industrial Archaeology, technical heritage

1 INTRODUCTION TO THE PROBLEMATIC

In a complex industrial context, where everything has to be done more and more quickly and must be more and more profitable, workers and industrial environments are transferred, transformed, etc. unused industrial machines are generally destroyed, or at best, stored. It is the technical knowledge of all humanity that disappears.
Today, Knowledge Management is a well-known application for enterprises. When we workd on knowledge, two requirements have to be taken into consideration (Thevenot 1998):

- a clear identification of the knowledge involved and the capacity of its management;
- the necessity to build and to use an identified methodology and a formalized process for its management.

Dealing mainly with implicit job knowledge – the so called know-how – (Amidon 2002), few methods exist proposing capitalizing of all the knowledge involved: product knowledge, process knowledge etc. and thus, from the product idea up to its industrialization, including the design phase.

Nowadays, the situation of technical and industrial heritage raises many problems: How can we manage and develop it in the context of museums and sites? How can we ensure life prolongation for the technical information of the collections, archives and heritage sites? This technical information, testimony of the past, is ageing very quickly; like a puzzle where parts wear or disappear, the technical data disappear progressively with the time.
Conservation of technical heritage encounters several major difficulties coming mainly from:

- a zero sensitization of the industrial world regarding the value of their technical heritage and their interest in the possibilities of heritage backup;
- financial difficulties to conserve, maintain and ensure the transportation of large size objects;
- a human difficulty due to the lack and the loss of the user consciousness and/or the disappearance of the machine designers and manufacturers.

The protection of scientific, technical and industrial heritage is a rather recent idea. It was in Britain, in the Sixties, that the concept of what British people call "industrial archaeology" was first introduced. The first experiment on an object for the capitalization and the popularization of heritage was the Ironbridge (this one was the first iron bridge, built in 1779 and classified as a UNESCO world heritage site in 1986) (Rolland 2001).
Generally, we rescue objects that are easily transportable or aesthetically correct. But artefacts that seem too complicated to conserve or that are not aesthetically correct are rejected. Moreover, for 200 years, objects have become more and more complex. Consequently, for the protection of this technical heritage there are still questions about the methods, the tools and the competences that have to be employed for capitalizing and popularizing it. In fact, new methods and new tools have to be defined for this museology of the 3rd millennium for doing better than we have in today's museums as Paul Rasse describes it (Rasse 1991): "Nowadays, in museums, we are very far from the factory and the workshop, the noise and dust, tiredness and sweat, […] the violence of the social relationships contribute to the history of technologies".

Understanding an old technical machine can be easy to achieve for former workers but it can be difficult and highly delicate for museum curators or visitors of the museum.
Consequently, a new question appears: what can be done with the industrial knowledge heritage on a local scale, a national scale or an international scale? Could methods and tools used in industrial engineering provide an answer to this new need: from the knowledge capitalization to the object digitalization going though the dynamic mock up to a virtual show? It is a new reverse-engineering process we propose to transpose from Industrial Engineering to Heritage: it is what we have called Advanced Industrial Archaeology.

In this paper, we will explain the methodology we have developed:

- First, the global process is presented;
- The second part describes the first part dealing with knowledge management and physical object capture;
- Next, we will concentrate on the 3D digitalization and the decision tree we have established;
- Finally, an example will demonstrate our proposal: from global capture to 3D digitalization for details; design, modelling and context understanding.

2 HYPOTHESIS

Considering that saving and maintaining physical objects is very costly for museums, and sometimes dismantling is nearly impossible as the machine crumbles to dust, our approach proposes a new kind of finality: we propose to preserve it as a numerical object. Consequently, engineers and industrial engineering tools and methods can give answers for the capitalization, conservation and popularization of old machines.
Our proposition consists in reversing the design time axis from end of lifetime back to the initial need. Thanks to a re-design by modelling of the technical machines and a contextualization in its environment, it can be possible to restore it for multiple finalities and more widely to restore the working situation of the socio-technical production system (Bernard & al 2002):

- control and measurement tools: from homemade measurement tools to laser scanning of the architects (systems with physical contacts, passive/active systems without physical contacts);
- design: from CAD tools to synthesis imagery;
- dynamic: technical machines with real kinematics with the representation of the flows, the fluids, the workers and the manufacturing environment;
- virtual visualization: from Web visualization to virtual reality;
- physical visualization: from the intermediate representation models of objects (Bouge & al 2002) thanks to rapid prototyping to a realistic and/or functional reconstruction of the machine.

Introducing new technology can be a real benefit for both museums and visitors. Usually, old machines do not operate or cannot be exhibited in a museum, so it could be a real and realistic new solution for capitalizing heritage. Globally, there is always the problem of cost and security to preserve the machine functionalities: components wear, the need of a machine driver etc. Consequently, using virtual technologies can be a real benefit for visitors and curators: Virtual Reality is a new mediation tool. Contrary to videos and thanks to interactivity, it is easier to understand the operating situation: the visitor is no longer a spectator but an actor. As he is immersed in the system, he can test the virtual machine to its limits. Moreover, the mediation-tool detail level can be adapted by the curators to the targeted public and thus make the machines come alive.

Figure 1 details the global overview process proposed. It demonstrates the interoperability possibilities between social sciences and engineer sciences. Two main steps can be deployed:

1. *Advanced Industrial Archaeology* → object and knowledge capture,
2. *Techno-museology* → popularization of the knowledge.

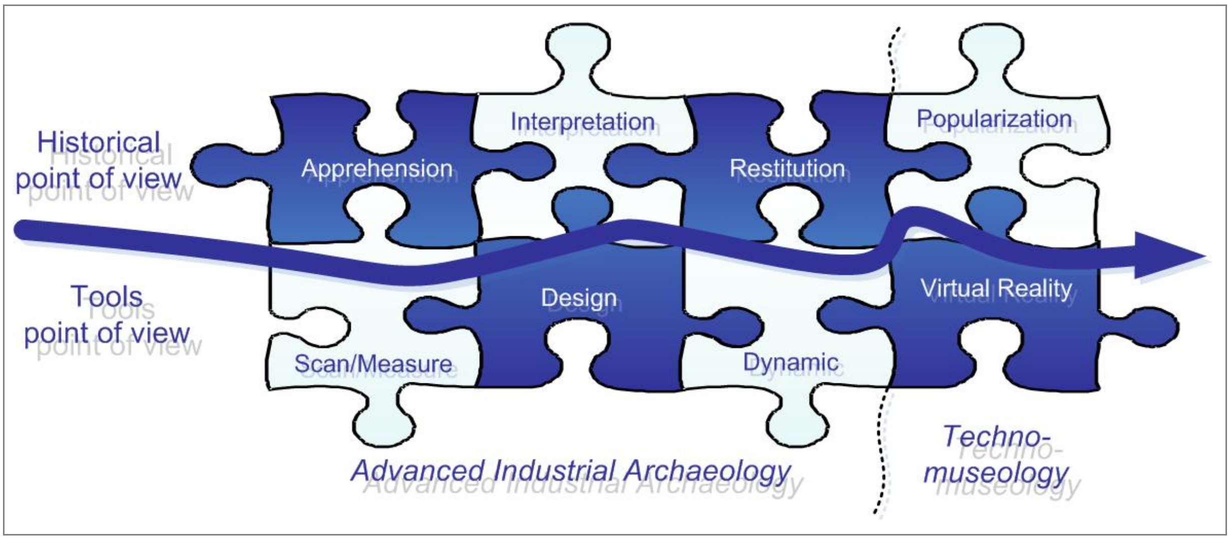

Figure 1: Global process methodology

The need is defined by the action chain resulting from technical history:

Apprehension → Interpretation → Restitution → Popularization

Apprehension is defined by the action of understanding, of grasping by perception, imagination, memory... Interpretation is defined by the action of giving an explanation or a meaning. Restitution is the fact of giving back something. Popularization consists in emphasizing. Popularization is a subclass of popularization: when popularizing, we allow everybody to have access to the object and its associated knowledge.

Tools and methods are defined by the digital chain from industrial engineering:

Information Capture (physical and textual) → 3D design → dynamic simulations (mechanical and Situations of use) → Virtual Reality applications

3 REVERSE-ENGINEERING PHASE

The purpose of this communication consists in establishing the basis of *Advanced Industrial Archaeology*. Consequently, we will focus on the first step of the process: the reverse-engineering phase. Figure 2 details the main steps that must be followed for virtualizing a physical object and associated knowledge.

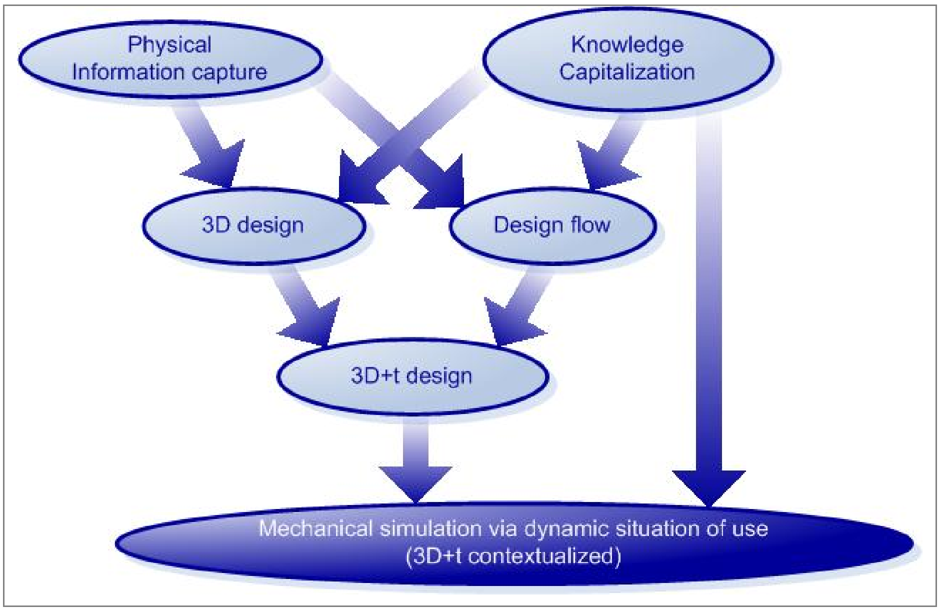

Figure 2: Reverse-engineering methodology

3.1 Definition of objects and knowledge involved

Before capitalizing knowledge (material or immaterial), it is necessary to identify the knowledge concerned. In this part of the paper, we will define what we call the material knowledge characterized by the real object of the industrial physical and the material and immaterial knowledge associated to it. As per terms of the APTE method related to the external functional analysis, this external knowledge can be defined as: the external environment of the object in its common use context.

The object taken in its intrinsic character, from a geometrical viewpoint, is a finite element which is fixed and limited. But the object relocated in its context cannot be considered as a finite and determined element, such as the intermediate object theory (Jeantet 1998), the object is a part of a dynamic, of a process where it can be:

- a raw material;
- a manufacturer;
- an intermediate component or a final component.

Within an epistemological framework, the object is defined as an artefact. According to the biologist Jacques Monod: "Any artefact is the product of a human being who expresses in a real obvious way one of the fundamental properties characterizing all the human beings: they are part of a project and they are representing within their structures and their performance achievement (for example, the creation of artefacts)." (Monod 1970)
Human industry can also be qualified as a production. The created artefact or the created object is qualified and quantified. It is part of the real world and presents a physical structure and a function (often associated with the performance concept). The object can be designed either from the structure towards the function or from the function towards the structure (FBS-PPRE model from Michel Labrousse (Labrousse 2004)). Consequently, humans will combine the two characteristics of the artefact by creating a functional physical structure. Following this definition, the artefact can be characterized by:

- its geometrical features related to the physical structure (points, lines, curves, surfaces and 3 dimensional volumes);
- its geometrical characteristics related to the function (points, lines, curves, surfaces and 3 dimensional volumes);
- its design features related to the function and the structure (we are speaking about internal mechanisms; for example, characterization of the physical properties and the chemical properties or even the colour which can also be associated with the chemical properties if it is one of the bases of the material);
- its aesthetic features (they do not interfere with the geometrical and technical definitions but aesthetic features complete these definitions; aesthetic features can be at a geometrical level or at a technical level; they can be selected without raw material justification).

Conserving technical machines means that the object but also its operating mechanism has to be capitalized by taking into account its technical and social context. Mechanically, operating is defined by functions and associated kinematics but also by processes and situations of use. Consequently, an object is considered as a technical and industrial one if it can be set in a socio-technical system. According to an epistemological point of view of the technical historian, an object must be contextualized so as to determine its value and to understand how it operates.

As in archaeology (we think about excavations of archaeological sites) the object can be represented by three aspects: a genesis, a life and a place, and this, within a double approach: material and intellectual (Reflexion 2006). Conserving only the physical object is not enough. This means that the object has to be contextualized by capitalizing the information, data, notes and know-how:

- at a technological and industrial level: in order to understand its operation and its insertion in industrial plants;
- at a social and economical level: so as to contextualize the object in order to determine the technological developments.

In his book "the life of objects", the anthropologist Thierry Bonnot states that "an object takes a meaning only in a human context" (Bonnot 2002). A machine or a system is significant only if it can relate to a social act and if it can help to conserve all the aspects of a technical culture, i.e. the physical objects but also the vestiges it contains: gestures, know-how, social relations etc. The object studied cannot be dissociated from its context (know-how, political context, social context, economic context etc.). Just like the photocopy gives back the object within its framework, the sound track on which has been recorded critical information for a better understanding of the object, or the written report where the human context has been consigned, all those elements enable the recontextualisation of the object (Rolland 2001). Consequently, depending on the desired finalities of the popularization, it will be advisable to capitalize all the necessary knowledge for achieving this goal.

Indeed, understanding and studying an old technical object requires large contextualization. Consequently, we will have to consider many various sources (Laroche & al 2006). Here are some examples of sources:

- machine drawings published by manufacturers;
- plant layout, cartography of the factory, physical mock-up;
- catalogues, patents, general documents of the manufacturer;
- handbooks, specialized reviews, World Fair reports;
- private industrial files or public funds (J series of the French departmental records);
- technical and industrial public files (M and S series of the French departmental records, public records);
- interviews, anthropological and sociological investigations;
- …

Sometimes, the physical object is in such an advanced state of deterioration that digitalization would be without interest or impossible as the object no longer exists in the industrial plant. That is why, if additional capitalized knowledge is sufficient, it will be possible to carry out an extrapolated virtual reconstitution, that will be more authentic.

3.2 Description of the methodology

According to figure 2, to create a digital model of an old technical object, several phases are required. The process consists in digitizing the object in order to immortalize it and to produce data that will be coherent, readable and transmissible to future generations.

Determining the state of the object

At the beginning of the study, the object life period that has to be represented in the digitalization process and the modeling process must be determined and detailed:

- "new" object, in its initial state of first use;
- object in use with possibilities of including adaptations and innovations;
- object at the end of lifetime;
- object in its archaeological state of discovery or when it was decided to preserve it;
- object partially extrapolated according to the gaps of State A.

Digitalization
If the object exists partially or entirely at the time of the study, it is possible to digitize it directly in three dimensions in order to collect its geometry. Several solutions of digitalization exist: laser scanning, photogrammetry, measurement systems with contacts etc. According to the size of the object, its material nature and its state of deterioration, the technologies used may be different. In the next part of this paper, we will develop the digitalization methodology we have set up.
It should be noted that if the object no longer exists, it will be possible to design an extrapolated model thanks to external documents and knowledge, (see paragraph before).

Re-designing: static components
The digitalized dots obtained have to be treated in order to be able to design the various components of the object. Taking into account the file size and the wish to create a realistic model, we would prefer solid design instead of surfacing.
Moreover, as modelling is costly in terms of time and money, it is necessary to specify the model accuracy level expected: screws, chamfers, precision for moulding parts etc It is the same problem as has been encountered with over-quality in manufacturing processes.

Re-designing: dynamic functions
As used objects are not inert, they are animated by mechanisms that have to be virtually restored and simulated in order to validate operating (Houten & al 2000). In the first step of the process A-B, it is essential to produce a functional virtual model that is mechanically realistic and as accurate as possible. That is why using CAD programs is better than using CG (Computer Graphics) programmes. CG programmes are usually used for creating animated pictures, movies etc. With CG programmes, simulations and dynamics are not realistic as a "world" is created in which one the objects will move but this world does not have the properties of the terrestrial physical laws such as the fundamental principles of mechanics (examples: gravity, stress, speed, acceleration). The digital mock-up will be realistic and not real; but as realistic as it can be (Eversheim & al 2000). Obviously, digital files will never replace physical objects: there is only one way to represent reality.
Many experiments we have done on technical heritage have led us to the model shown in figure 3 (Laroche & al 2005).

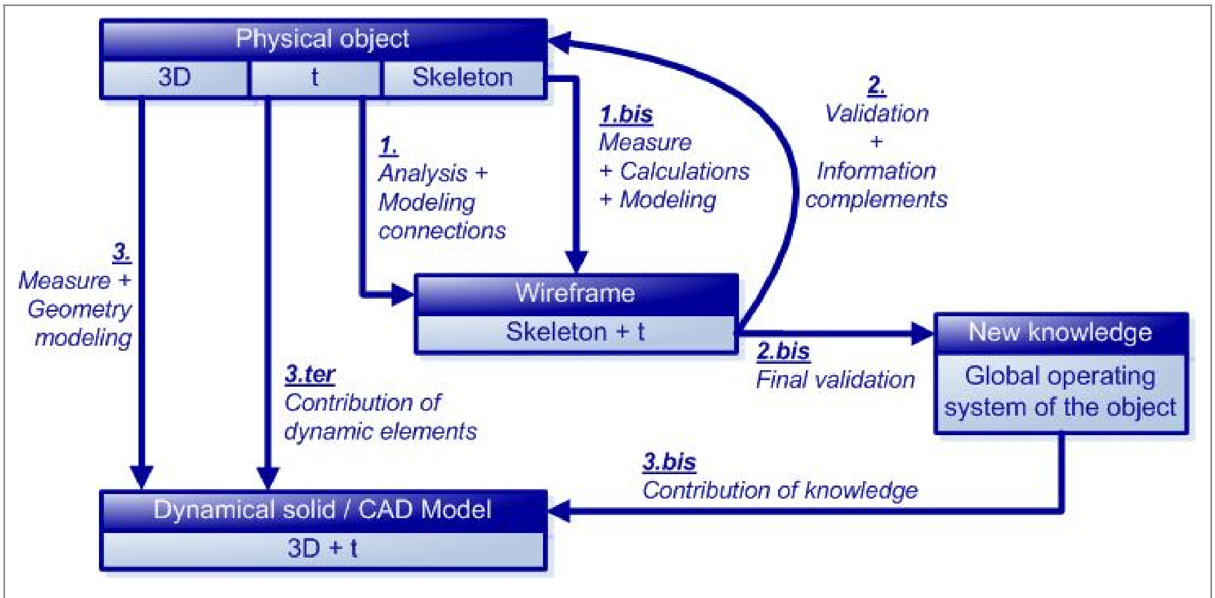

Figure 3: Method for modelling old systems

The physical object is separated into its 3D components, its skeleton and the "time" concept. Time "t" will create the dynamic situation.

Methodology associated to figure 3 is:
1. *an object skeleton has to be designed;*
2. *adding the concept of time, it will produce a kinematic sketch; drawn in 3D space, it will produce a wireframe that has to move back-and-forth with the physical object in order to validate it and to fix the dynamic;*
3. *the last step will produce new knowledge maturation: the mechanism understanding;*
4. *next the dynamic digital model is created by anchoring solids on the skeleton.*

Environment and other dynamic flows
Except for kinematics, simulations are carried out in post-processing and without direct visualization. For example, this is a problem for modelling fluids: in the case of a steam engine, it is actually very difficult to visualize the steam exchanges inside CAD software. However, such visualization is essential for curators and all non-expert people.
It will also be necessary to consider the need of environmental restitution of the machine: actuators and motors, the nearest machines, the industrial plant, etc. Do they have to be digitized and modelled?

Materials and other aspects
An object is defined by its geometrical characteristics ("3D") and its kinematic functional properties ("3D+t"). But functionalities could also be due to the material properties used: it is necessary to carry out a virtualisation of materials.
In the same way, materials or paintings are design information that could be essential for a future restitution and that must be taken into account during the digitalization step.
Where are the limits of the external appearances in relation to the concept of authenticity? Is it necessary to restore false colours to prove virtuality?
With regard to design, an object can be characterized by its colourimetric but also by auditive and olfactive perceptions: how to capitalize on sounds and odours in digital form? Notice that this information has sometimes disappeared with the dismantling or the non-possibility of operating the machine.

4 3D DIGITALIZATION

In order to resolve the problem of patrimonial object conservation, we have to capture physical data if it exists. The first basic tools are: decametres, slide callipers, micrometer callipers. However, in order to optimize cost and time, for measuring complex machines, 3D digitalization can be employed: TMM laser radar, X-ray, 3D scanner laser with topographical reconstruction in real-time.
Firstly, in this part, we will give the state-of-the-art of the different technologies that can be found on the market or new technologies resulting from fundamental research that will emerge in the near future and that will answer the problems of 3D digitalization of patrimonial objects. We distinguish between active systems and passive systems: the main difference is due to the technology used as it emites a light beam or not.
Moreover, as we usually work with old objects, contact can be sometimes impossible or even forbidden. The best solution has to be identified clearly and the choice must take into account external constraints from environmental surroundings. The last paragraph of this part will explain the methodology we have developed for choosing the best tool.

4.1 Systems with physical contacts

The following are the basic measuring instruments that have been used for a long time:
- decametre,
- slide calliper,
- micrometer calliper, etc.

There are also many mechanical palpation systems that are almost automatic and are usually combined with a canned jib controlled by a computer. Some of them are named TMM for Three-dimensional Measurement Machines. But the most important difficulty is that the object to measure has to be brought into the laboratory, as those measurement systems are usually not movable. Moreover, they need many settings in order to be efficient and measuring is very slow. However, they can be effective on large objects: from 0.5 m^3 to 115 m^3.

4.2 Passive systems without contact

Usually used for graphic design, these systems are passive without contact since they capture information with photographic systems or stereoscopic systems. The acquisition tools are cameras and movie cameras.

Photographic systems enable 3D models to be built rapidly thanks to high definition digital photos. The associated process is:

1. *detecting common points between photographs,*
2. *automatic distance calculations and 3D wireframe design,*
3. *textures application using photographic definition,*
4. *automatic virtual camera or virtual video camera positioning.*

It is necessary to state for the model precision that depends of the camera definition: the more accurate the camera is, the more the model will be accurate.

4.3 Active systems without contact

Active systems without contact are technologies that generate short waves for measuring; for example: the laser. According to the object size to be digitized, there are various solutions:

- “desktop“ laser scan: box containing the scanner. Accuracy = 0.1 mm. It is suitable for only small size objects,
- TMM laser radar. High speed, high accuracy,
- 3D scanner laser. For example from Minolta. They are the most popular and are used for medicine, industrial engineering, archaeology, etc.
- X-ray tomography systems,
- Interferometer with optic fibres,
- Optic measuring system

4.4 Classification

The technology that will be used depends on the dimensions to be acquired (...$<1m^3<$...$<10m^3<$...$<60m^3<$...), and on the desired accuracy, the acquisition time available and the possibility to handle/move the object. Consequently, dealing with the digitalization of patrimonial objects, it would be advisable to combine the technologies (active/passive systems with/without contact) in order to optimize the acquisition chain (e.g. without contact due to serious state of deterioration).

Moreover, our classification takes into account the numbers of handling actions that have to be done in order to get the whole 3D model. If only one angle is considered, it will return only a stereographic view. Consequently, it is necessary to combine various views and/or various kinds of scanners. For instance, during the Computer Aided-Design-Manufacturing & Measurement Integration conference, Boeing presented a multiple-scanner digitalization system that is used for controlling wing dimensions (Richey & al 2001).

In order to use it within its context, i.e. taking into consideration the object conditions and what can be done or not with the patrimonial object, we have established a decision tree (figure 5). Based on criteria, it helps to find the best solution for digitalizing the object within the time available, the precision needed... They are two kinds of criteria:

- The operability factors that result from the technology to be used (figure 4),
- The data related to the object state (figure 5).

Relevance of measurements?	Firstly, it is necessary to decide the necessity, or otherwise, of digitizing the whole object. For example, in the case of a crane, it would be a waste of time capturing all the girders since they are identical.
Object full-scale?	If the object is incomplete or does not exist, missing parts can be designed according to the designer's knowledge, the external knowledge and know-how.
Palpation?	Possibility of palpation of the object.
Relocating?	Possibility of relocating the object.
Radiations?	Possibility of exposure to radiation: technologies using various wave-lengths (infra-red, visible, X-ray...); sometimes, due to its state of deterioration, the object would not be able to tolerate certain wave-lengths.

Figure 4: The main factors related to operability

The material	Define the object material.
Accessibility	Sometimes measurements have to be made from vision angles that are not accessible or even those that are inside the object.
Size/volume	The size of the object and the volume that has to be digitized.
Kinematic digitization	The desire to capture its state at work.
Time taken for digitization	When many points have to be captured, some methods have to be eliminated.
Accuracy	It interacts directly with the digitization time and the results of the digitization.
Handcrafted or industrial object	An object coming from a domestic system needs the definition of more points, as not all the parts are the same.

Figure 5: The initial data from the characterization of the object itself

For example, linking various factors like digitalization time, size, craftsmanship... if we want to digitalize a chair, is it necessary to reflect upon the relevance of capturing the entire geometric definition of the chair? Only major points have to be considered: lines can then be drawn between those points and the adjoining surfaces and volumes can be designed. See figure 6.

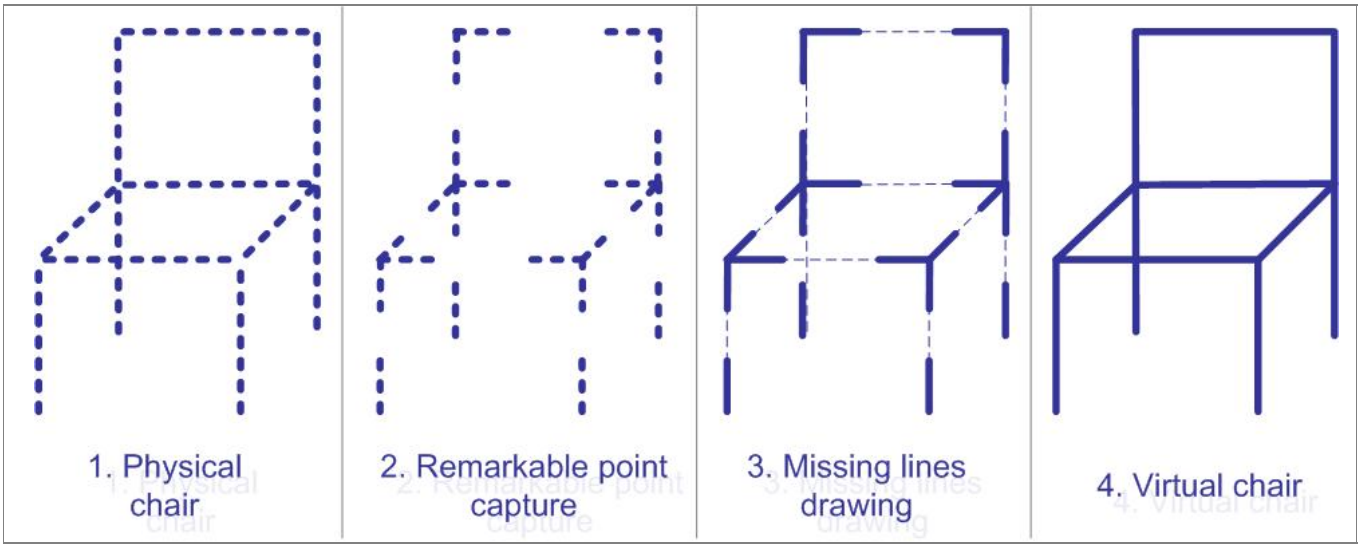

Figure 6: Chair design using a cloud of points

The following figure 7 sums up tools explained previously and the way to choose the optimum technology. All digitalization tools explained or developed previously are not mentioned but the main solutions are proposed. The nodes represent questions that must be asked. However, please note that the method found by the decision tree may not be the only one but it is probably the best one to use. If another strategy is chosen, it will be more costly and will impact accuracy, efficiency or acquisition speed.

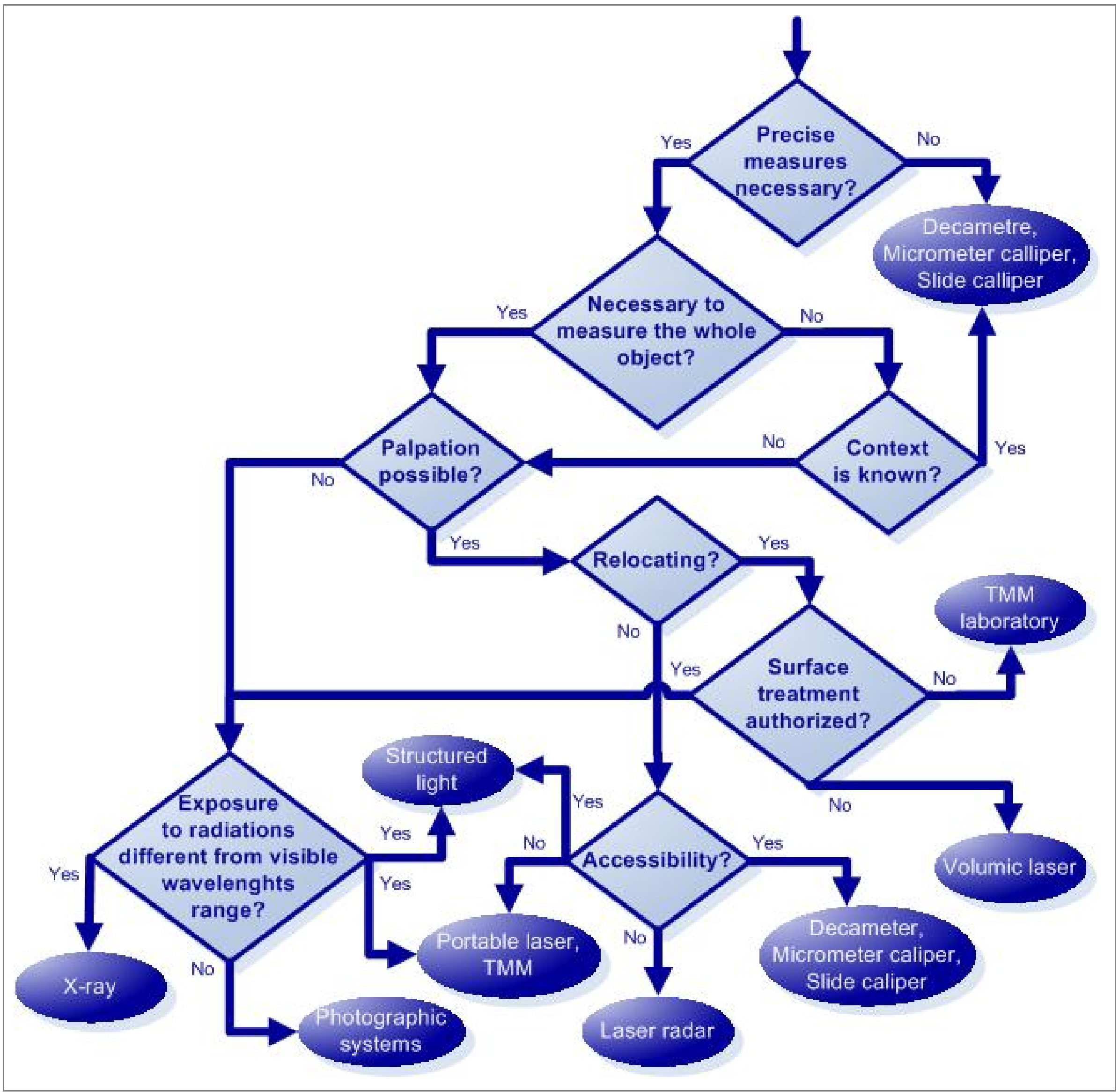

Figure 7: The decision tree for choosing the best digitalization practice

5 SALT-WASHING MACHINE: FROM 3D DIGITALIZATION TO TECHNICAL AND HISTORICAL STUDIES

The experience detailed in this part is a study that began 20 years ago and which is the result of a meeting with an industrial technical object: a handcrafted machine of the 20th century. Thus, through the study of the Bertrand family business from its social origins to its production system, its management and its marketing of salt, our investigations led us to define the global Technical System that has nowadays become a Patrimonial System: it is much more than an industrial machine that must be considered, it is a site, a region, a complex economy that explains its unique place in France. We have to state that this salt store which is 130 years old and has a surface area of more than 400 m² is soon to become the new Salt Marsh's Museum of Bretagne, which has recently been recognized as a Musée de France (Godin 2006).

5.1 Background

In 1984, the Salt Marsh Museum opened in Batz-sur-Mer in Loire-Atlantique in France (44). It is the successor to the Museum of Ancient Costumes, one of the first Civilization Museums in the west of France, founded in 1887 in Batz.
The museum offers a permanent exhibition on 250 m² which combines history and memory to interest all kind of public. Ethnographic collections, documentaries and Fine Arts recount the technical and human adventure of salt panning, from its origins to the present day, and presents the discovery of the rich heritage of this area shaped by 2000 years of salt history. This collection presents:

- Furniture, costumes, ceramics, household items, engravings, paintings, postcards… all a testimony to the past,
- Tools used in the past for the salt work, but also physical models… for informing the visitor about the traditional techniques of human workers of yesterday and today.

With a surface area of 400 m², the museum receives about 30000 visitors annually. But, at the opening of the new museum, there was a problem of storage space for the non-exhibited collections or those acquired by donations, as well as the lack of a place for temporary exhibitions.
In 1987, faced with this lack of space, the Museum curators were looking for new buildings. They found an architectural unit of 2 900 m². Built in granite of the region with a wooden floor and a slate roof, the industrial building had been used for storing salt.

Figure 8: Photo of Bertrand storehouse (2007)

Inside the main building, there was a machine made of wood and metal (latitude 47°16'44.37" north and longitude 2°28'41.33" west). First analyses indicated that it was dealing with a product that had caused the machine to deteriorate over time: salt. A conservation and investigation phase began to study this object and to understand its integration into its complex techno-industrial system.
The sight of this machine in a state of ruin at an advanced stage created a special atmosphere and those involved in this project immediately fell *in love* with it. Many questions were raised and many hypotheses put forward about its operations, its construction, its uses…: *Why a salt-washing machine? Why salt? How does salt washing operate? What is it for? Why did this machine stop operating? Why are there no more salt machines?*

5.2 Object discovery and first representations

A primary health status has revealed that the object disintegration is inexorable. Thus, as it deteriorates very quickly, the machine first has to be immortalized. To do this, numerous photographs have been taken by the Museum curators.
Notice that the object dimensions are big: the base covers about 20 m² and the height is 3.25 meters.

Figure 9: Photograph of the salt-washing machine (2007)

To complete this first photograph collection and to help to understand the technical process, freehand drawings are done (Buron 2004). But we have to point out that they are not technical drawings: some details are extrapolated and may not be technologically feasible.

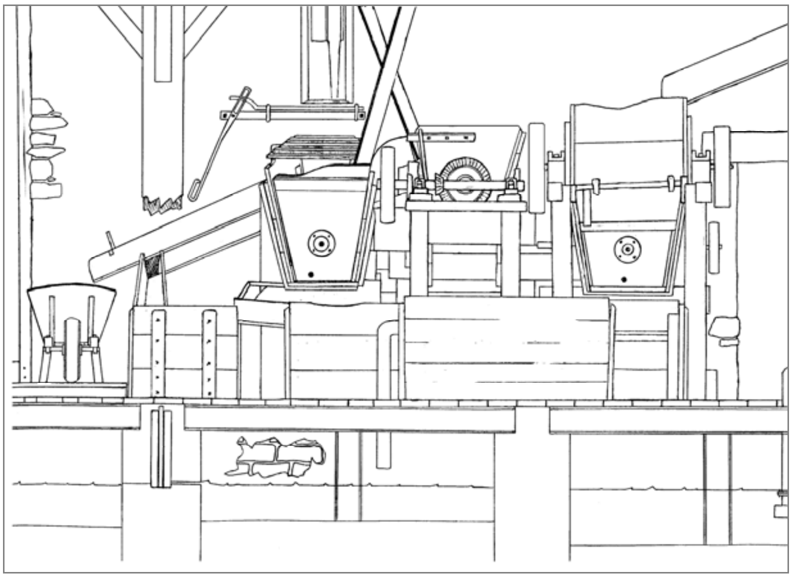

Figure 10: Architectural drawings of the salt-washing machine

5.3 Technical drawings and 3D digitalization

We then had to understand how the machine operates and how it was built 90 years ago. To do this, other technical intermediary sketches were done (Derouene 2005).

Figure11: Mechanical freehand drawings

Moreover, in order to contextualize the machine in its architectural framework at a precise date, a second project produced a 3-dimensional photograph. According to the methodology proposed and explained previously in this paper, we have defined the 3D digitalization technology that has to be used.

Main factors	
Relevance of measurements?	Capital for immortalizing the object as it destroys itself more and more everyday.
Object full-scale?	Yes
Palpation?	Impossible
Relocating?	Impossible
Radiations?	All wavelengths that do not destroy wood.

Object datas	
The material	Not reflecting but not in bad conditions.
Accessibility	Some components hidden by other ones; moreover, walls prevent seeing some views.
Size/volume	approximately 120 m^3
Kinematic digitization	No
Time taken for digitization	Unlimited in a short time but digitalisation has to be done quickly (machine deteriorates more every day).
Accuracy	linked with the handicraft status of the object
Handcrafted or industrial object	Handcrafted, impossible to copy and paste components, the global machine has to be digitalized.

Figure 12: Defining the 3D digitalization technology for the global capture

Consequently, following the decision tree of figure 7, a portable laser was chosen. The global digitalization was carried out by the Architectural firm, Morel Mapping Workshop. The scanner laser is a Leica Cyrax 2500. It is possible to obtain 1 point every 1 mm from a distance of 100 meters. However, in our project, a better precision was obtained as the scanner was at a maximum of 10 meters from the machine.
Figure 13 presents the cloud of points obtained. The accuracy is 0.3 cm for 10 039 374 points scanned.

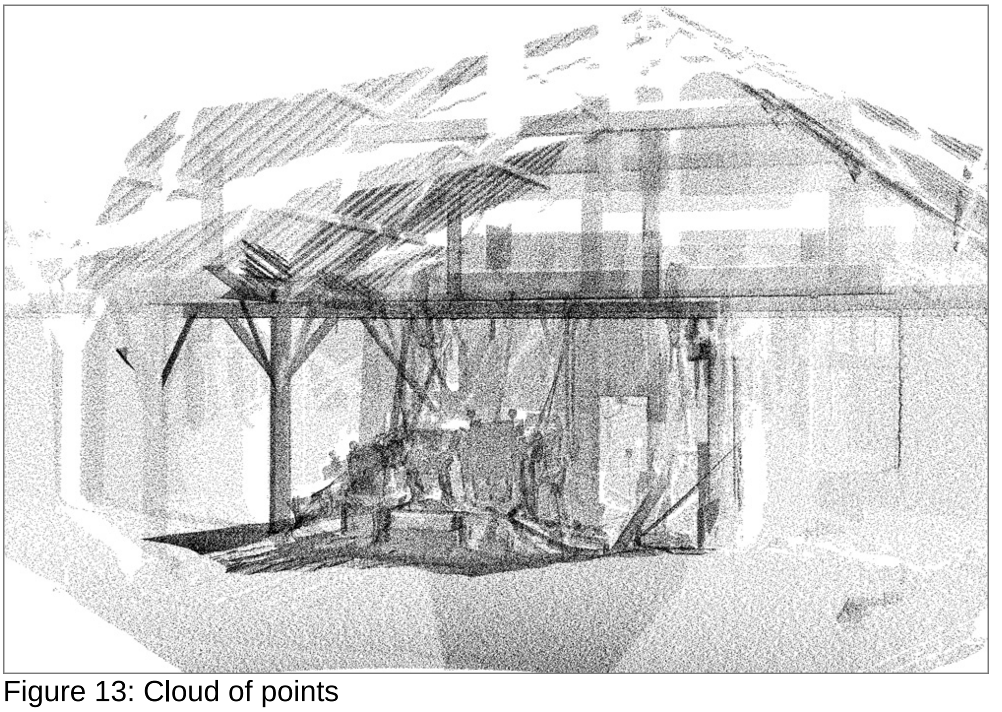

Figure 13: Cloud of points

5.4 Mechanical design study

Once the cloud of points has been obtained, several solutions exist for using data: export the points to a CAD software, point-to-point direct measurement, automatic geometry rebuilding. Rebuilding the geometry can be carried out automatically by pattern recognition. This solution is particularly adapted to standard elements such as cubes, tubes or simple surfaces (car wings, etc.) However, in the case of the salt-washing machine, this solution was not possible due to the advanced state of deterioration of the object, which would have distorted the automatic form recognition.
Consequently, we have manually designed the machine using the clouds of points. Finally, there are more than 550 components.

From a technical point of view, we have divided the object into five functional parts corresponding to a step sequence describing the operating process of the machine. Each element will act upon one or several flows. Like a nuclear power plant, there are three flows:

1. *The primary flow: the salt;*
2. *The secondary flow used as a moderator to deal with the primary flow: the brine;*
3. *The tertiary flow for supplying the power force of the machine.*

The salt goes first into the bucket chain and then into the hopper. It finishes its treatment inside the trays. The entire process is performed thanks to a second solution: the brine, an aqueous solution which is salt saturated. Mechanical machineries are powered by an energy source which is a rotation movement. The following table 14 correlates these flows with the major components of the machine located in figure 15:

1. *The engine and the main shaft;*
2. *The bucket chain;*
3. *The hopper;*
4. *The washing trays;*
5. *The circulation system of the brine.*

Generated flow	Flow description	Parts / components involved	Function
Primary flow	Salt	Bucket chain	Feeding the machine with raw materials 2
		Hopper	Salt crushing 3
		Trays	Treatement 4
Secondary flow	Brine	Tank	Circulation system 5
Tertiary flow	Energy force	Motor	Powering the machineries of the primary and secondary flows 1
		Main shaft	
		Secondary shaft	
		Pump	

Figure 14: Flow description and major components of the salt-washing machine of Batz-sur-Mer

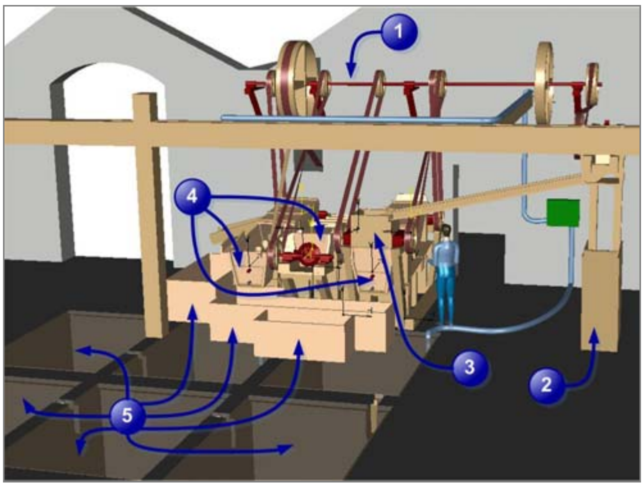

Figure 15: CAD model, overview of the machine

❶ The engine and the main shaft

The engine manufactured by Cardner is housed in the boiler room near the main building. It provides energy required for all the mechanisms of the machine. At first, a belt coming from the engine distributes a rotation movement to the main shaft. On this shaft, other belts are rolled up to a wooden pulley and are connected to the numerous mechanical components of the machine. Belts are very thick, made of linen and looped by metal staples. To prevent them from slipping on the pulleys, they are regularly coated with resin.

Initially, the engine must be a gas engine. Next, the energy power is replaced by an electric motor manufactured by AO. The engine is still in an archaeological state.

❷ The bucket chain

At the beginning of the process, the salt is shovelled into the well filled with brine. In the same well, the chain - equipped with buckets - leaves the pit vertically. The salt rises in a liquid state (figure 16). Arriving at the highest point, the solution is poured into a gutter and finally drops into in the hopper positioned above the first tray.

The chain and the buckets come from an English patent based on a system called Ewart. Figure 17 is an extract from the elevator catalogue of the Burton Son factory that proposed this kind of technology. It is dated August 1893 (Burton Son 1893).

Figure 16: Photograph, Bucket chain (2007)

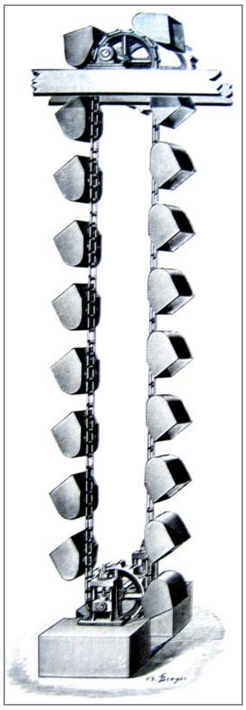

Figure 17: Burton Son catalogue, Ewart chain (1893)

❸ The hopper

The liquid solution flowing down from the gutter goes inside the hopper. The hopper has two metal cylinders rotating in opposite directions: the salt is crushed into numerous fragments.

❹ The washing trays

The central part of the machine consists of three trays placed in series. They are inclined at 6° from the horizontal and are positioned in opposition.

Each one is crossed by an axis on which blades are inserted. The axis and blades create a group similar to an Archimedes screw as used for purging water in mines. The liquid solution passing through the hopper falls into the lower position of the first tray. Blades push the solution up to the other end of the tray, in the upper position. Next, a small gutter carries the solution into the next tray, in the lower position. Finally, the saline solution is collected at the end of the 3rd tray thanks to a final gutter larger than the other ones. It has a double floor: the higher one is made of linen and allows the salt solution to drain out at the end of the washing process.

Figure 18 sets up the overall process and the front view emphasises the double floor of the final gutter. It should be noticed that today, this gutter and the hopper gutter have collapsed.
Each tree is driven by bevel gears which are operated by a belt connected to the main shaft. The amount of salt accumulated on the metal elements as well as the action of salt over time have considerably damaged the gears.
However, to achieve our research in Advanced Industrial Archaeology, historical documents were an important resource. It is interesting to note that in its 1893 catalogue the French manufacturer, Burton Son, sold these mechanisms that are called angle wheels.
Consequently, it is possible that the inventors of the salt-washing machine bought buckets, chains and bevel gears from the same supplier.

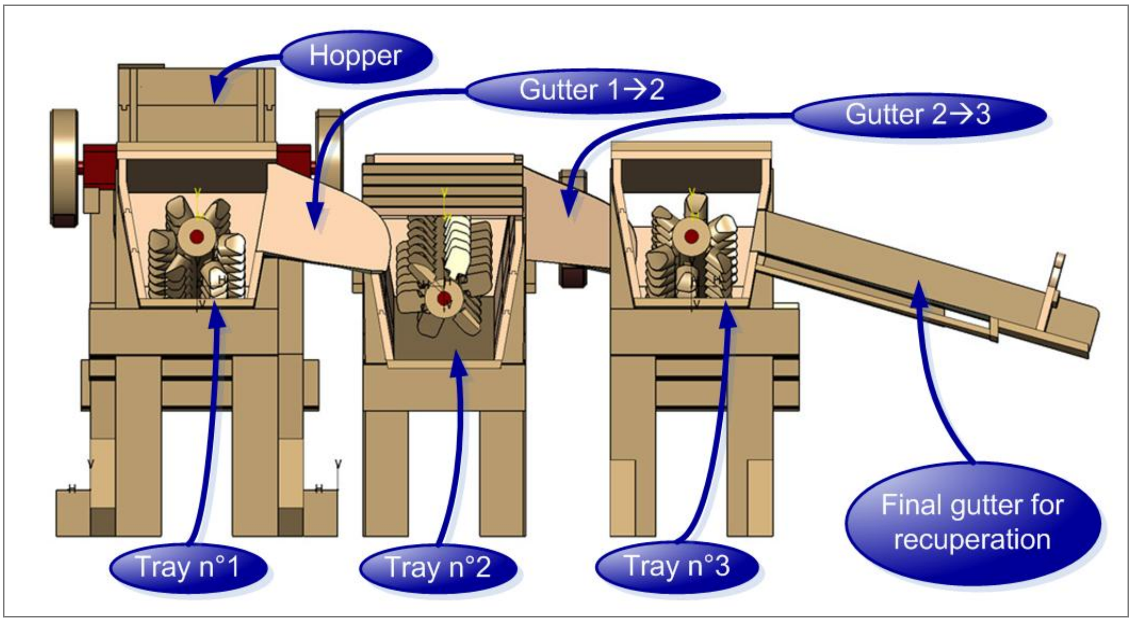

Figure 18: Front cross section view of the 3 trays and the final gutter

❺ System circulation of the brine
The second and the third trays receive brine from an air pipe system. After use, the brine is recycled. It is decanted into 3 small tanks located a few centimetres lower than the level of the machine. After that, it falls into 6 successive underground tanks where it terminates its purification phase. At the exit of the last tank, the brine is pumped and then injected again thanks to the pipe system (figure 19).
Tanks form rectangles of 3x2 meters and are 1.70 meters deep. To allow free movement of employees inside the building, the tanks are covered by wood and metal mobile plates. The tanks are connected by a system of gates. These openings are roughly 15 cm wide and 50 cm high. Sediment traces currently residing in the tank reach a thickness of 50 to 70 cm. Consequently, we can suppose there were many maintenance problems to ensure regular removal of the sludge.

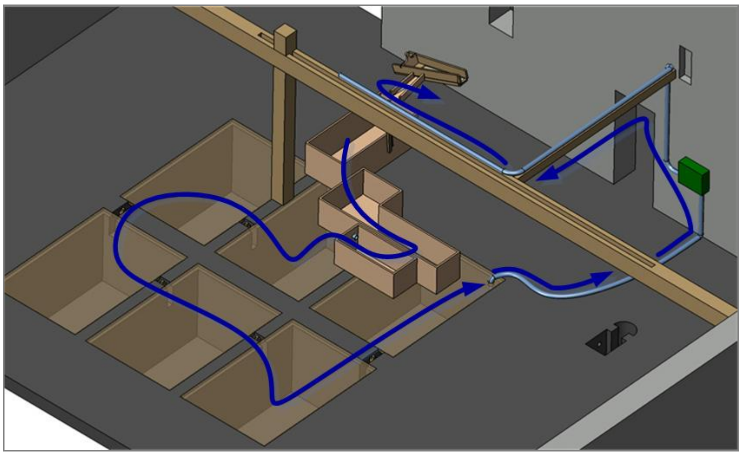
Figure 19: CAD model of the circulation system of the brine

5.5 A perpetually deteriorating craftsmanship machine?

At the end of this first mechanical study and thanks to the dynamic 3D modelling, we have validated the historical hypothesis suggesting it is a handcrafted machine. If the trays seem to be similar, each one is different. The virtual model takes into account this mainframe and authenticity; otherwise the CAD software cannot operate the machine virtually.
In addition, some elements exist nowadays only as wreckage lying on the ground around the machine. These elements have been designed virtually, taking into account the form of components with which they were in contact, but also thanks to the mechanism study.
Moreover, we have to notice that, the machine has had sealing problems as the numerous salt piles show it. Small repairs have surely been done. That is why a few parts have been:

- reinforced by a doubling of wooden plates;
- or replaced: for a same component, the quality of the wood plate can be different from the nearby plate.

As a testimony to this craft industry, the building housing the engine still contains two very old pieces of furniture: a storage unit (used as spare parts store) and a workbench (carpenter shop).

In the same way, during the engine study, ground excavations revealed a mechanical object that could not be linked to the electric motor or its predecessor. It is a bearing that holds the gear axes, the pulleys or the hopper cylinders.

This bearing is less deteriorated than other ones still positioned on the machine; we can think about the possibility of spare parts (figure 20). Nevertheless, it has many blisters on the surface; it confirms the hypothesis that long-term exposure to a saline and moist atmosphere has attacked the cast iron inside. The interior diameter of a new bearing measures 40 mm while gear axes and pulleys axes measure 80 mm. These elements demonstrate that salt action has led to metal deterioration, either since the machine was built or since operations were stopped. This deterioration can be described as extreme (figure 21).

Figure 20: Photograph of unused bearing (2007)

Figure 21: Photograph of bearing and distorted axes (2007)

5.6 Mechanical study assessment

Once the operating of the machine was understood, a kinematics sketch of the machine was realized into CATIA V5 software (distributed by Dassault Systemes).
After having created the skeleton and the connections, a check was carried out to see whether the virtual model had been simulated therefore functional. Then volumes were added to the skeleton in order to obtain a full-scale and realistic model. Volumes were obtained thanks to the cloud of points.
Finally, the virtual model of this machine is composed of more than 550 parts and 30 kinematic link-ups.

Thanks to all the elements explained previously about the internal study of the machine, we are now able to validate the objective of this industrial artefact: "Washing the salt by dissolving it in a saturated saline solution."

But there are still some problems to evaluate the machine production as there are uncertainties about the engine: no speed, no information about the provided torque, etc. That is why we have conducted excavations with a 3D scanner and external studies about the socio-economic and ethnological environment of the machine to identify the human context surrounding the Bertrand enterprise, trader in sea salt.

5.7 Detailed characterization of the salt-washing machine components using archaeological excavations and 3D digitalization

Some parts essential for the machine to operate could not be scanned by the Leica scanner:

- the worm blades of the trays because they are inside the machine;
- the salt production flow: the links and the buckets.

Both elements are currently in an advanced state of deterioration. However, the geometric and structural characteristics of these components are essential when determining the production capacity of the salt-washing machine.

The bucket chain has nearly been completely destroyed by the salt: it is not yet suspended and its components form a pile of rusty material that we have investigated. Unable to be measured with modern tools as it would have caused too much damage, those new measures have been carried out thanks to a new 3D technology. However, parts may not be removed from the wetness-saturated atmosphere. The reaction caused by a hydrometric change would be so great that the parts would have deteriorated even faster. So, we chose to digitize the parts under optimal conditions for their preservation but extreme conditions for the 3D sensor. Application of the decision tree based on the initial data of the object and the main factors as shown in table 22, the solution used is a portable scanner which is more precise than the Leica scanner: the Handyscan is distributed by Creaform (www.handyscan3d.com).

Based on a Canadian patent, the scanner is self-positioned in 3D space using reflecting targets. It is possible to scan the same point many times to optimise its position. The accuracy is of about 0.2 mm, but it mainly depends on the volume of the object that has to be digitalized.

Main factors	
Relevance of measurements?	Required for getting the exact characterization.
Object full-scale?	Worn or damaged
Palpation?	Impossible
Relocating?	Yes if no destructive
Radiations?	Possible if staying in an atmosphere with the same hydrometric rate.
Object datas	
The material	Not reflecting but not in bad condition.
Accessibility	Some components are inside the machine but can be dislodged.
Size/volume	Maximum: cube of 200 mm side
Kinematic digitization	No because unitary part
Time taken for digitization	Unlimited in a short time but digitalization has to be done quickly (machine deteriorates more every day).
Accuracy	More precision possible for obtaining exact geometric characterization
Handcrafted or industrial object	Handcrafted for the blades / Industrially made for the links and the buckets.

Figure 22: Defining the 3D digitalization technology for detail capture

As the links are completely rusty and no more complete buckets exist, 3D scanning has enabled us to obtain multiple virtual representations (figure 23). By average iterations over all scans, the generic dimensions were calculated. Then, we compared this information with the data from the 1893 Ewart catalogue. It is a vertical elevator with a device for adjusting the chain tension. It is composed of quick-links and special links with two ears for connecting the buckets. They are manufactured by stamping and are usually recommended for flour. The average volumetric capacity of a bucket is 1.5 litres. The

standard operating range for the Ewart links is 36 Newton with a yield point of 90 Newton and a tear resistance lower than 180 Newton.
It should be noted that this kind of chain is still used in contemporary industrial workplaces, but its patent has fallen into the public domain.

Figure 23: Links with ears: a physical and virtual object made of cloud of points

In addition, other detailed studies have helped us to refine our advanced industrial archaeology studies. Thus, hidden under a pile of sand, salt and dust, we found blades inside holes of the workbench (figure 24). These blades have sharp edges and the presence of a file on the workbench confirm that they were being manufactured and that minor repairs on the salt-washing machine took place directly on site, probably by the workers themselves. Bigger repairs were carried out by the town carpenter.

Figure 24: Photograph showing blades manufactured on the workbench (2007)

We have also scanned those original components and have compared them with those installed on the machine. We were thus able to validate their original dimensions while the machine was operating. In figure 25, it is possible to distinguish saw lines captured by the Handyscan. The digital file is made of a mesh of 112 815 points.

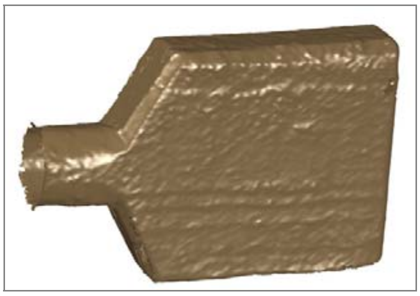

Figure 25: Cloud of points of an original blade

5.8 Experimentation assessment

The industrial heritage study undertaken thanks to archaeological excavations has demonstrated the potential of the methodology of advanced industrial archaeology. It shows the importance of making interactions between the object and its background for refining the internal studies integrating external knowledge. The approach developed in this example illustrates the funnel effect: a progressive un-zoom is applied to understand the subject and the outcome is the definition of the global Technical System.
A classical study would have only concentrated on research on the salt-washing machine and would have introduced a dichotomy between internal and external uses. However, we have analyzed the object in its multi-dimensional and multi-temporal aspects. It can be summarized by two main points:

- A product: the salt;
- A process: the collecting and the salt treatment.

We can validate the raison d'être of the salt-washing machine and the environment in which it operates: "In order to be able to respond to the demands of the hygienist clientele of the 19th century and to defend itself faced with increasingly fierce competition, traders had to refine salt. All local enterprises built salt-washing machinery that could be considered as personal inventions. Occupying about twenty square meters, the Bertrand salt-washing machine was made of wood and metal; it is currently in an advanced state of deterioration. It was operating from 1914 to 1966, the year the company closed. The aim of washing sea salt is to eliminate soil particles and then, by mixing it with a saturated solution of salt, the saturated solution absorbs the particles separating them from the "good" salt. "
In terms of the efficiency of the Bertrand production site, coupling mechanical analysis and historical data enable us to validate the capabilities of the production steps (figure 26).

Salt pans	Buckets	First gutter	Hopper	Trays	Wheelbarrow / Final gutter	Storage	Transport to the station
3000 tons min. / year	-	-		-	9000 tons / year	6000 tons maximum	7000 tons maximum
-	12 m^3/min	19.2 m^3/min	1.6 m^3/min	1.7 m^3/min		-	-

Figure 26: Monitoring the salt production flow of Bertrand Enterprise in Batz-sur-Mer

In the salt marshes of Batz-sur-Mer, there were approximately 20 salt-washing machines; however, only one remains: the one preserved in the Bertrand enterprise. Surveys conducted by the Museum curators show that in 1941 only two machines were still in operation.

6 Conclusion

In this paper, we give details of our research subject dealing with the conservation of scientific and technical heritage. Focusing upon old objects such as industrial machines, our proposal is to virtualize them for a better understanding of its knowledge.
Several finalities are possible; for example:

- virtual thesaurus (digital archives),
- safeguards in industrial archaeology,
- didactic use for experts or students,
- reconstruction,
- museum popularization for any kind of public.

For the last application case, thanks to the exponential growth of Virtual Reality technologies, several approaches can be developed and could bring new hope for museums.
At the beginning of the process, knowledge capitalization is necessary: the context and obviously the artefact itself: it is a contextualized reverse-engineering process. In order to respect the patrimony, 3D scanning technologies have to be selected and manipulated carefully. The decision tree can help us to choose the best solution.
Nowadays, knowledge developped by enterprise belongs to explicit or implicit know-how and are orientated for design or process; however, daily innovations remain at a local level. Breaking innovation is much more difficult to accomplish and requires new tools and new methods with various kinds of knowledge and competences. Using old technical knowledge can be a solution for creating new

products. It is in this way of "thinking the future" that our team performs its research. However, instead of working on present objects, the starting point is technical objects belonging to the past.

7 Acknowledgments

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- Philippe Lhériteau, student architect, Architecture School of Nantes.

8 References

Amidon D. M., 2002, *Innovation et management des connaissances*, Editions d'organisation, 226 p.

Bernard A., Hasan R., 2002, *Working situation model as the base of life-cycle modelling of socio-technical production systems*, CIRP Design Seminar, conference proceedings

Bonnot T., 2002, *La vie des objets – d'ustensiles banals à objets de collection,* Editions MSH, 244 p., ISBN 2735109348

Bougé P., Champin P.-A., 2002, *Une représentation épisodique des connaissances pour l'assistance à la réutilisation en CAO*, 13th French Knowledge Engineering Workshop, conference proceedings, 175-183

Buron G., 2004, *Petite histoire des magasins de la Croix de Paix et de l'entreprise Bertrand de négoces de sel / Little story of the storehouse Croix de Paix and the salt enterprise Bertrand*, 19 p.

Burton Son, 1893, *Catalogue of elevators, convoying apparatus and transmission*, Paris, France, 31 p.

Derouene L., 2005, *Realisation of a dynamic CAD model: the washing machine of Guérande*, Engineer training period report, UTBM, Belfort, France, 45 p.

Eversheim W., Schenke F.-B., Weber P., 2000, *Virtual engineering for an integrated product and process development*, CIRP Design Seminar, conference proceedings, 111-116

Godin, M., 2006, *Salt March's museum: a social dimension*, Ouest France Journal, 25 april 2006, 1 p.

Jeantet A., 1998, *Les objets intermédiaires dans la conception. Eléments pour une sociologie des processus de conception*, Sociologie du Travail, pp. 291-316

Labrousse M., 2004, *Proposition d'un modèle conceptuel unifié pour la gestion dynamique des connaissances d'entreprise,* phD thesis, Ecole Centrale de Nantes, France

Laroche F., Bernard A., Cotte M., 2006, *Methodology for simulating ancient technical systems*, International Review of Numerical Engineering, Integrated Design and Production, Vol. 2 n°1-2/2006, pp.9-28, Hermès-Science, Ed. Lavoisier, ISBN 978-2-7462-1679-2 - riin.revuesonline.com

Laroche F., Le Loch S., 2005, *Culture technique et CAO par les machines anciennes*, CETSIS, conference proceedings, 6 p.

Monod J., 1970, *Le Hasard et la nécessité*, Éditions du Seuil, Paris, France, p.25

Rasse P., 1991, *Communication et muséologie des techniques*, REMUS, conference proceedings, ISBN 2-11-08753218-23

Reflexion, 2006, *www.archeologia.be*, web site seen the 01/05/2006

Richey M.C., McIvor R.S., Sandwith S.C., 2001, *Computer Aided-Design-Manufacturing & Measurement Integration,* Proceedings of Coordinate Measurement System Committee, Albuquerque, Mexico, 7 p.

Rolland-Villemot B., 2001, *Le traitement des collections industrielles et techniques, de la connaissance à la diffusion*, OCIM letter n°73, pp.13-18

Thevenot D., 1998, *Le partage des connaissances : une mémoire interactive pour la compétitivité de l'entreprise,* Editions Tec & Doc, Lavoisier, 136 p.

Van Houten F.J.A.M., Kimura F., 2000, *The virtual maintenance system: a computer-based support tool for robust design, product monitoring, fault diagnosis and maintenance planning*, Manufacturing Technology, CIRP Annals, 49/1, 91-94